Fermilab

Doc Number:	Beams-doc-4982
Version:	1.0
Category:	Note

Aperture Implications for Recycler Assuming Full Coupling and Nominal Vertical Apertures

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16 October 2015

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Abstract

In order to specify the apertures needed for Recycler Collimators and Masks, we will explore the vertical aperture requirements implied by the nominal vertical beam pipe size and examine the lattice functions to find the largest vertical beta. For horizontal aperture requirements we will assume full vertical to horizontal coupling and add to this a requirement for the momentum spread and slip stacking offsets. To these requirements an allowance for injection errors will be added to arrive at an aperture requirement. Using a nominal beam emittance of 15 pi-mm-mr and the same momentum spread and slip stacking momentum requirements, we will determine the nominal beam size. The amplitudes required to move this beam edge to the aperture edge will set the maximum bumps needed for collimation. Since collimators will define apertures inside of the Recycler aperture, the bump amplitudes for collimation will be smaller than determined here. This is not a specification document but it will describe the basis we will use to define collimation system requirements.

*Operated by Fermi Research Alliance under contract with the U. S. Department of Energy

1 Introduction

The Fermilab Recycler is now employed as a accumulation ring for 8 GeV protons to provide high intensity beam to inject into the Main Injector. With the available beam quality from the Booster, we have losses for all operating scenarios but studies of slip stacking indicate higher losses with these modes. To localize these losses, we are designing a collimation system which is expected to absorb protons which are outside the acceptance of the ring and the secondaries produced when those protons interact in large steel blocks. For designing this system we need to know the boundaries for beam which is transmitted through the limited vertical aperture of the Recycler, and compare that aperture to the expected beam size in order to understand the magnitude of potential orbit bumps required to move beam into the collimation system. We will use a nominal Recycler lattice and a tentative collimator placement for which we will document the important geometry.

2 Recycler Characteristics

The Couraant-Snyder lattice parameters we will employ come from the R90 Console Program. We employed R90 file 16 from 8 September 2015 to obtain a lattice description. The lattice included preliminary descriptions for a number of potential primary and secondary collimator locations and many potential locations for dipole corrector magnets. Using the text output from R90 we loaded this description into an Excel spreadsheet (RRApertureForBeam.xlxs) to calculate beam properties. This ‘design’ lattice has been compared with measurements and found to be in reasonable agreement. We choose not to add an allowance for the difference between ‘design’ and ‘measured’ lattice to our already conservative assumptions below.

2.1 Vertical Beam Size

We assume that the principal limitation is in the vertical acceptance due to the standard beam pipe height. This will manifest itself at the largest β_y around the ring. In this lattice file we find $\beta_{peak} = 58.6$ m. For the maximum aperture we use $y_{pipe} = 20$ mm. The internal beam pipe height at the center is a bit more than 22 mm but there are many welds at high β_y so we assume that this should cause us to assume a smaller maximum available size. The vertical boundaries will then be

$$y_{max}(s) = \frac{\sqrt{\beta(s)}}{\sqrt{\beta_{peak}}} y_{pipe} \tag{1}$$

$$y_{min}(s) = -\frac{\sqrt{\beta(s)}}{\sqrt{\beta_{peak}}} y_{pipe} \tag{2}$$

Using typical Booster 95% normalized beam emittance of $\varepsilon = 15$ pi-mm-mr we calculate typical RMS vertical beam sizes from

$$\sigma_y(s) = \sqrt{\frac{\varepsilon \beta_y(s)}{6\, \beta_{rel} \gamma_{rel} \beta_{peak}}} \tag{3}$$

where β_{rel} and γ_{rel} describe the proton relativistic motion. From this we find a three sigma boundary

$$y_{up}(s) = 3\sigma_y(s) \tag{4}$$

$$y_{down}(s) = -3\sigma_y(s) \tag{5}$$

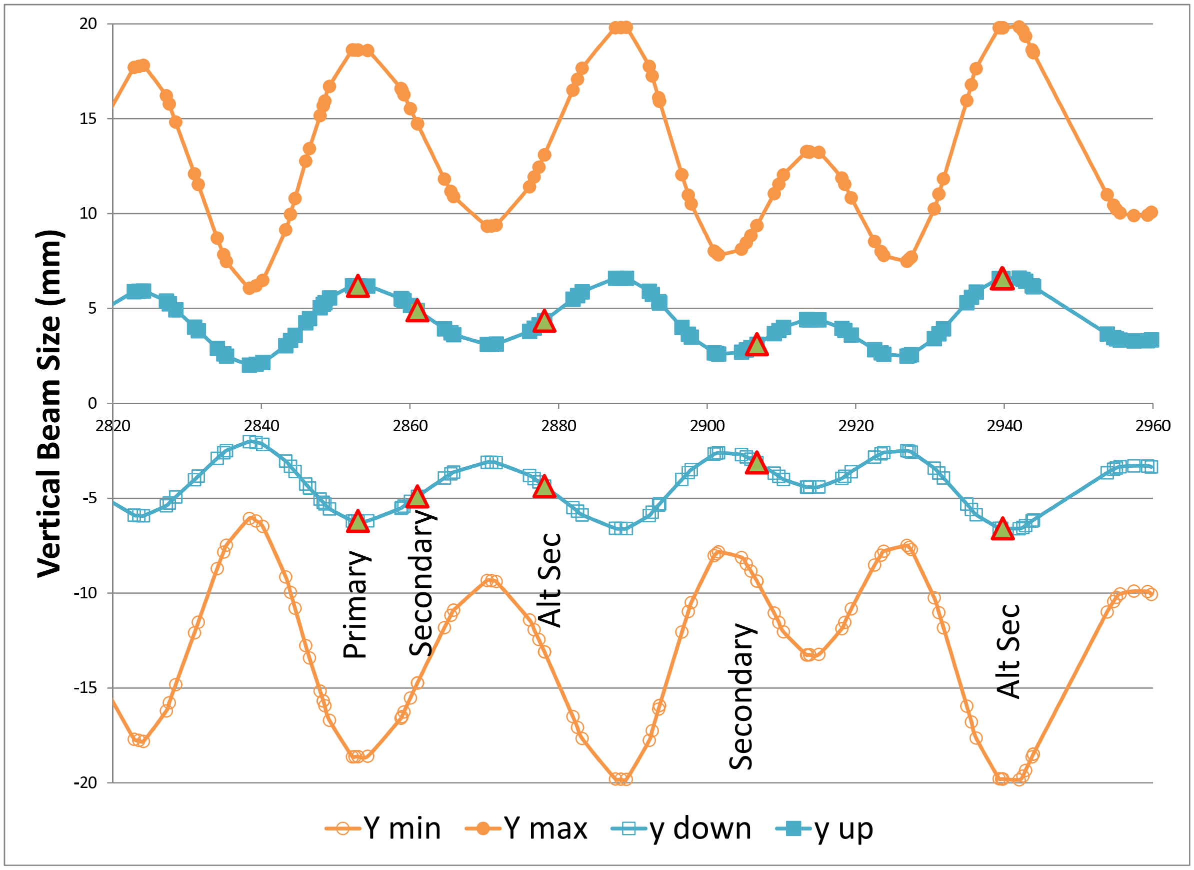

Figure 1: Vertical beam properties in the region from RR611 to RR620 are shown. The orange curves mark the upper and lower vertical boundaries of beam acceptance. Beams which can circulate through the vertical aperture limit at the maximum beta will fit inside of these boundaries after correcting injection offsets. The blue curves describe the beam envelope for 15 pi-mm-mr beam. Red with green triangles mark positions under consideration for collimation.

For the region from RR611 to RR620 where the collimators and collimator bumps are planned, we show the typical beam size and boundaries of accepted beam in Figure 1. Locations under consideration for collimation are identified with green triangles with red outlines. These include a primary identified in the spreadsheet as PCOLL613B and Secondary Collimators identified as SCOLL613D and SCOLL616 (for initial phase of collimation - 2016) and potential additional Secondary collimators (Alt Sec - potential second phase installation) at SCOLL614 and SCOLL619U.

2.2 Horizontal Beam Size

For each injection from the Booster (at 15 Hz), the injected beam will circulate for about 6000 turns before the next injection. We assume (round beam) that some combination of linear (skew quadrupole) and non-linear coupling will mix all the beam vertical and horizontal motion and especially so for the beam at the boundaries. This assumption implies that we calculate the horizontal betatron beam size with the same parameters as for the vertical beam size.

To this we must add a contribution for momentum effects. Two contributions are of interest. The longitudinal admittance for 15 Hz slip stacking contributes an RMS momentum spread of 3.5 MeV/c for injected beam which can be accepted. The 20 Hz Booster operation may allow a larger admittance which we will take as 4/3 larger or 4.667 MeV/c. For each of the slip stacked beams we will calculate a horizontal beam sigma which is the RMS of the betatron RMS and and momentum RMS. For an 8 GeV or 8.889 GeV/c beam these imply $\frac{\sigma_p}{p}$ of 0.000394 (15 Hz) or 0.000525 (20 Hz).

$$\sigma_x(s) = \sqrt{\frac{\varepsilon\beta_x(s)}{6\,\beta_{rel}\gamma_{rel}\beta_{peak}} + (1000\,\eta\frac{\sigma_p}{p})^2} \tag{6}$$

The factor of 1000 is because we express beam sizes in mm. Before calculating the positions of the beam edges, we will calculate the displacement of the beam caused by the momentum offset for slip stacking. This is determined by the time available for slipping and is $dp = 24.5$ MeV/c ($dp/p = 0.276\%$) for 15 Hz Slip Stacking or $dp = 32.66$ MeV/c ($dp/p = 0.367\%$) for 20 Hz Slip Stacking.

$$x_{\text{ssoffset}} = 1000\,\eta\,\frac{dp}{p} \tag{7}$$

The 3 sigma edges for the beam at momentum center are given by

$$x_{in}(s) = 3\sigma_x(s) \tag{8}$$

$$x_{out}(s) = -3\sigma_x(s) \tag{9}$$

For the beam which is decelerated for slipping, the edges are

$$x_{\text{off-in}}(s) = x_{\text{ssoffset}} + 3\sigma_x(s) \tag{10}$$

$$x_{\text{off-out}}(s) = x_{\text{ssoffset}} - 3\sigma_x(s) \tag{11}$$

For the maximum horizontal beam size we will be more conservative by adding the momentum width, momentum offset, and betatron sizes linearly. We seek to know the size we need to leave when we build new devices. Slip stacking may employ beam on momentum center along with decelerated beam (Spring 2015 option) or on center with accelerated beam (possible future option) or we may inject off center and displace the slipping beam from that orbit. We will never use the aperture we describe with this calculation but it will allow full flexibility for future decisions.

$$x_{max}(s) = \frac{\sqrt{\beta(s)}}{\sqrt{\beta_{peak}}} y_{pipe} + 1000\,\eta\,(dp + \sigma_p) \tag{12}$$

$$x_{min}(s) = -\frac{\sqrt{\beta(s)}}{\sqrt{\beta_{peak}}} y_{pipe} - 1000\,\eta\,(dp + \sigma_p) \tag{13}$$

The horizontal beam features are illustrated in Figure 2. Again we show typical beam size and boundaries of accepted beam but the beam boundaries are shown both for on momentum beam and beam decelerated for slipping. Also shown as (x offset) is the beam center (momentum orbit) for the decelerated beam

3 Boundaries at Proposed Collimator Locations

With the above formulas implemented in the spreadsheet RRApertureForBeam.xlxs, we can find the expected beam sizes and maximum beam sizes for the proposed collimator locations. will provide the spreadsheet with momentum parameters for 20 Hz slip stacking but for 15 Hz values, the user can substitute in the two cells as desired.

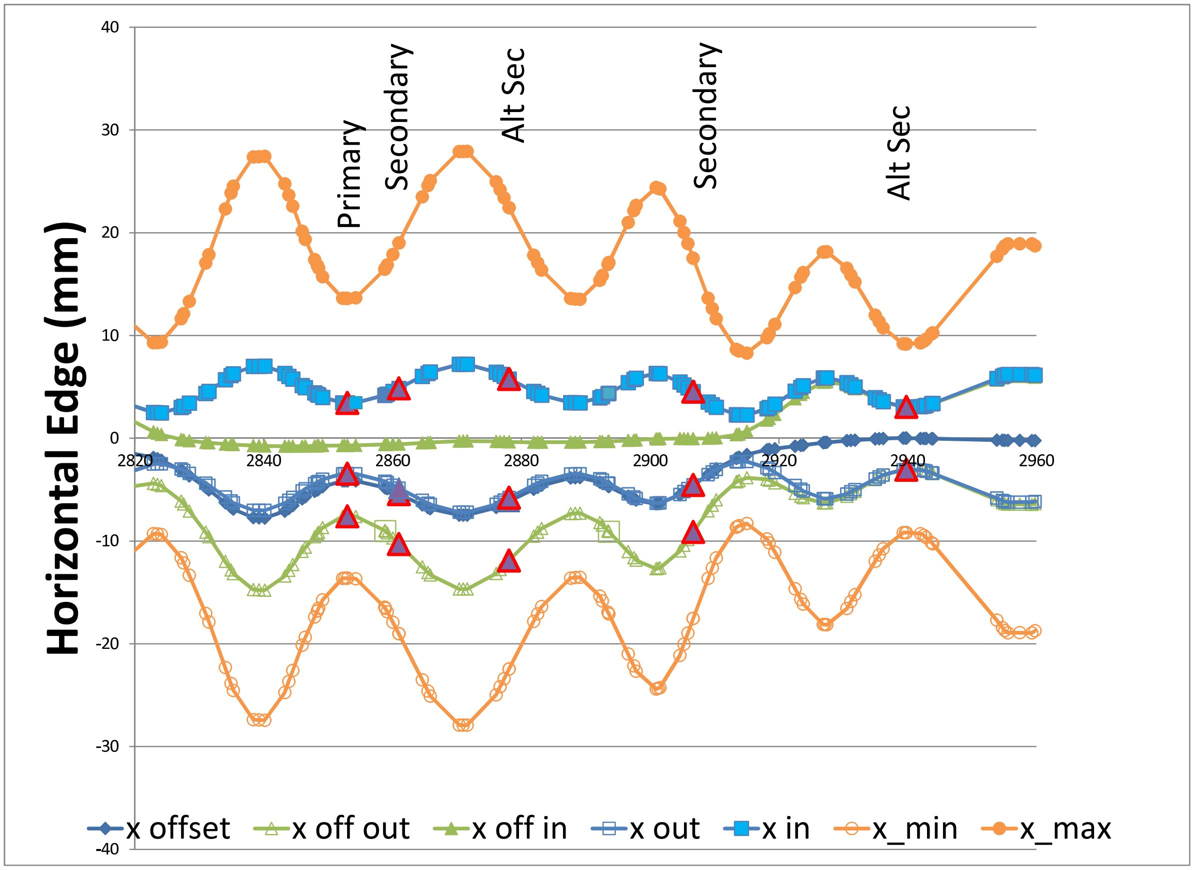

Figure 2: Horizontal beam properties in the region from RR611 to RR620 are shown. Assuming full coupling, beam which circulates through the vertical aperture limit at the maximum vertical beta will fit within the orange curves after correcting injection offsets. Blue curves show the beam size for 15 pi-mm-mr beam with the momentum width allowed by slip stacking acceptance. The green curves show the same beam which has been displaced for slip stack slipping. The x offset curve shows the displacement of the beam center for the slipping beam (momentum orbit for slipping beam). We see that the edge of the on momentum beam is at the center (offset beam position) of the slipping beam.

3.1 Vertical Boundaries

For the vertical boundaries, we can put everything in Table 1. The position of the largest vertical displacement we can require at each location is y min or y max. We see that this is a bit smaller than the 20 mm size we assume for the beam pipe inside aperture. We suggest that an allowance for injection steering errors of up to 3 or 4 mm should be added to this. We can consider whether the appropriate vertical size of a collimator should be uniform or whether smaller collimation apertures corresponding to y max as small at 9.37 mm might permit a reduced external activation.

For designing bumps, we see that the required displacement also varies by x2 and while that does go with the Beta at the collimator, one needs to design specific bumps to see what magnet strength is needed.

Table 1: Vertical Lattice and Beam Boundaries and Maximum Bump Amplitude

Name	Station	phase	Beta	Alpha	y dn	y up	y min	y max	y max - y up
	m	Rad/2π	m		mm	mm	mm	mm	mm
PCOLL613B	2853	20.93	50.746	0.04275	-6.193	6.193	-18.612	18.612	12.418
SCOLL613D	2861	20.96	31.782	1.7997	-4.901	4.901	-14.729	14.729	9.827
SCOLL614	2878.1	21.12	25.12	-1.65082	-4.358	4.358	-13.095	13.095	8.738
SCOLL616	2906.7	21.34	12.849	-0.9175	-3.117	3.117	-9.3651	9.3652	6.248
SCOLL619U	2939.8	21.66	57.391	-0.04248	-6.587	6.587	-19.793	19.793	13.215

3.2 Horizontal Boundaries

We need to display the horizontal information in more tables to keep them of manageable size. For finite beam momentum spread, the dispersion (η or Eta) increases the beam size. But more importantly, we will be working with slip stacking momentum offsets of one of the beams. We consider that in one direction and exhibit the required displacements. The vertical collimation will impact both beams. With the preferred two secondary collimator solution, we will seek to collimate the on momentum beam. Only by adding at least one of the alternative collimators will it be possible to provide horizontal scraping for the offset (slipping) beam. Perhaps the collimator vertical boundaries will be sufficient to control beam halo. In Table 2 we show the lattice parameters with the RMS beam size and the slip stacking displacement.

Table 2: Horizontal Lattice, beam size, and offset for 20 Hz Slip Stacking

Name	Station	phase	Beta	Alpha	Eta	Etap	sigma	x offset
	m	Rad/2π	m		m		mm	mm
PCOLL613B	2853	21.797	11.514	-0.004	-1.131	0.0006	1.149	-4.154
SCOLL613D	2861	21.885	24.034	-1.630	-1.478	-0.07923	1.619	-5.431
SCOLL614	2878.1	21.949	34.967	2.0269	-1.667	0.08288	1.924	-6.124
SCOLL616	2906.7	22.164	22.163	2.1675	-1.246	0.12183	1.513	-4.579
SCOLL619U	2939.8	22.530	12.372	0.0459	0.003	-0.00354	1.019	0.011

The boundaries for 15 pi-mm-mr beams displaced for slipping or on momentum center are shown along with the maximum beam extent due to betatron beam size, momentum beam size and momentum displacement for slipping (20 Hz slip stacking) are shown in Table 3. We see that there is significant overlap between the 3 sigma widths of the displaced and centered beam. Again, we suggest adding 3 or 4 mm to allow for injection errors.

4 Observations and Conclusions

The primary collimator should have a width of at least 2×13.6 mm (See Table 3. Note that we will bump the beam into this after damping and do not need to add an allowance for injection errors. The horizontal beam position at the primary is unconstrained. But we observe that changes in the horizontal beam position at the first secondary (SCOLL613D) will necessarily change the horizontal position at the primary. These position changes fall within the limits for the primary size

Table 3: Horizontal Boundaries for 20 Hz Slip Stacking

Name	Station	x off out	x off in	x out	x in	x min	x max
	m	mm	mm	mm	mm	mm	mm
PCOLL613B	2853	-7.6004	-0.7081	-3.446	3.446	-13.613	13.613
SCOLL613D	2861	-10.288	-0.5741	-4.857	4.857	-19.016	19.016
SCOLL614	2878.1	-11.897	-0.3514	-5.773	5.773	-22.449	22.449
SCOLL616	2906.7	-9.1189	-0.0396	-4.540	4.540	-17.533	17.533
SCOLL619U	2939.8	-3.0473	3.0692	-3.058	3.058	-9.1772	9.1772

Table 4: Horizontal Displacement Requirements

	Results for 20 Hz		Results for 15 Hz	
	x max - x in	-x min + x off out	x max - x off out	-x min + x off out
	mm	mm	mm	mm
PCOLL613B	10.16	6.01	9.19	6.07
SCOLL613D	14.16	8.73	12.86	8.78
SCOLL614	16.68	10.55	15.19	10.6
SCOLL616	12.99	8.41	11.88	8.44
SCOLL619U	6.12	6.13	6.12	6.13

specified above.

The secondary collimators for the Main Injector employed an aperture of 2 inches by 4 inches. This is over generous. We used 2 inches by 2 inches in the MI8 collimators and this looks to be adequate for the Recycler Collimation. The required minimum size (with these assumptions) can be determined from (y max)-(y min) in Table 1 and (x max)-(x min) in Table 3 and that is in some cases much smaller. The motion provided for the secondary collimators will accommodate larger collimator apertures. Perhaps we can learn how much advantage a smaller aperture provides when seeking to contain the activation within the secondary collimators by employing MARS calculations.

5 Acknowledgments

I would like to thank Ming-Jen Yang and Phil Adamson for many discussions and suggestions.